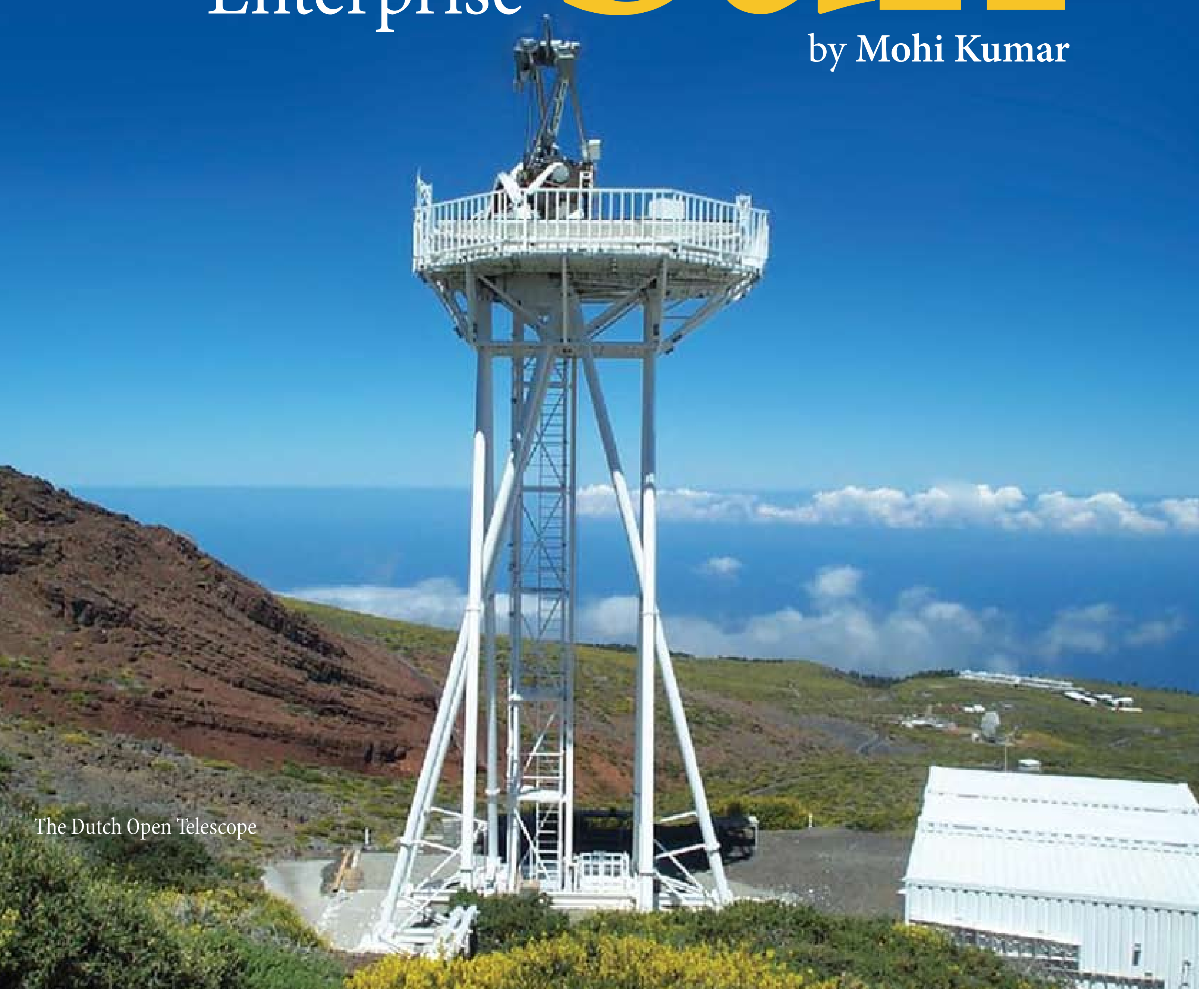
Monitoring the Sun

A Global Space Weather Enterprise

by Mohi Kumar



The Dutch Open Telescope

Hurricane watch, air traffic control, the simple switch of a light. As society's dependence on satellite information, global positioning systems, and electrical generation rises, countries around the world face increased risk of disruption and damage to vital infrastructure and communications and navigation networks due to adverse space weather. To combat this, nations are joining collaborative efforts to monitor the Sun from the ground in real time, helping to produce space weather forecasts and nowcasts.

"Space weather is very much a global issue and much can change during the time when a single ground-based solar observatory is not in daylight," said Alexi Glover, the coordinator of the Space Weather European Network (SWENET), a service that collects and provides operational and monitoring products to countries in the European Union. "Excellent results can be obtained when facilities located in countries spread across a range of longitudes collaborate."

Past articles in this series focused on milestones in space weather science and overviewed ground-based solar observatories in the United States. Below are brief summaries about leading solar observatories outside the United States. The combined data from all facilities can provide fuller, more detailed pictures of adverse space weather across the globe.

Royal Observatory of Belgium

Founded in 1826, the Royal Observatory of Belgium (ROB; see http://www.astro.oma.be/) was one of the first institutions dedicated to studying the Sun. Early research highlights from the observatory include the thorough *Etude du Spectre Solaire* (Atlas of the Solar Spectrum), a study consisting of 2400 hand-drawn emission lines in the visible part of the solar spectrum, completed by Belgian scientist Charles Fiévez in 1882.

In the early twentieth century, ROB scientists began capturing images of the Sun's photosphere with newly developed photographic technology that projects solar images onto a disk, allowing researchers to draw and record sunspots.

In 1954, scientists constructed a new instrument, fully automated with solar sensors and motor-driven photographic cameras. Called the Uccle Solar Equatorial Table (USET), the instrument carries three independent refracting telescopes. The first is a modernization of the original telescope: a 150-millimeter white-light telescope that projects an image of the photosphere on a screen for visual sunspot drawings. This telescope is one of 85 stations on a worldwide network geared toward monitoring sunspots, as part of the International Astronomical Union's Sunspot World Data Center. The second telescope in USET is a 150-millimeter white-light telescope that images the corona, and the third is a 110-millimeter telescope that images the Sun using the hydrogen emission spectrum, allowing for detailed observations of the solar surface.

Data from USET are accessible in real time through its Solar Influences Data Analysis Center (SIDC; see http://sidc.oma.be). "We are currently in the process of upgrading our aging cameras," said Frédéric Clette, a scientist at ROB responsible for ground-based solar operations. "With future cameras, we would like to also develop a local flare-alert capability."

Up until the early 1980s, the Swiss Federal Observatory in Zurich regularly produced the Zurich sunspot number, a data set that guided governments on the status of space weather because the frequency of sunspots is a quick indicator of solar activity. In 1981, however, Zurich discontinued this service. Answering a strong request from the scientific community to continue monitoring sunspot activity, ROB assumed this responsibility. Today, the SIDC assimilates USET data with data from other collaborators to publish daily, monthly, and yearly international sunspot numbers (Figure 1) in addition to its other duties.

ROB also hosts a radio astronomy station in southern Belgium, consisting of 48 parabolic antennas. Operations at this array have temporarily halted while ROB builds an improved spectrographic radio observation center at this location, with the goal of providing radio burst diagnostics and alerts to the European community, Clette said.

European Northern Observatory

Located on La Palma and Tenerife, two of the Canary Islands, the European Northern Observatory (http://www.iac.es/eno/) consists of a series of telescopes run by several European nations whose grounds are managed by Spain's Instituto de Astrofísica de Canarias (IAC). Officially founded in 1985, the network's location hosts a high degree of atmospheric clarity, making it the second best location for optical and infrared astronomy, after Hawaii's Mauna Kea observatories. The observatory is the home of several instruments geared toward developing a better understanding of solar magnetics, a factor important to space weather models and forecasts.

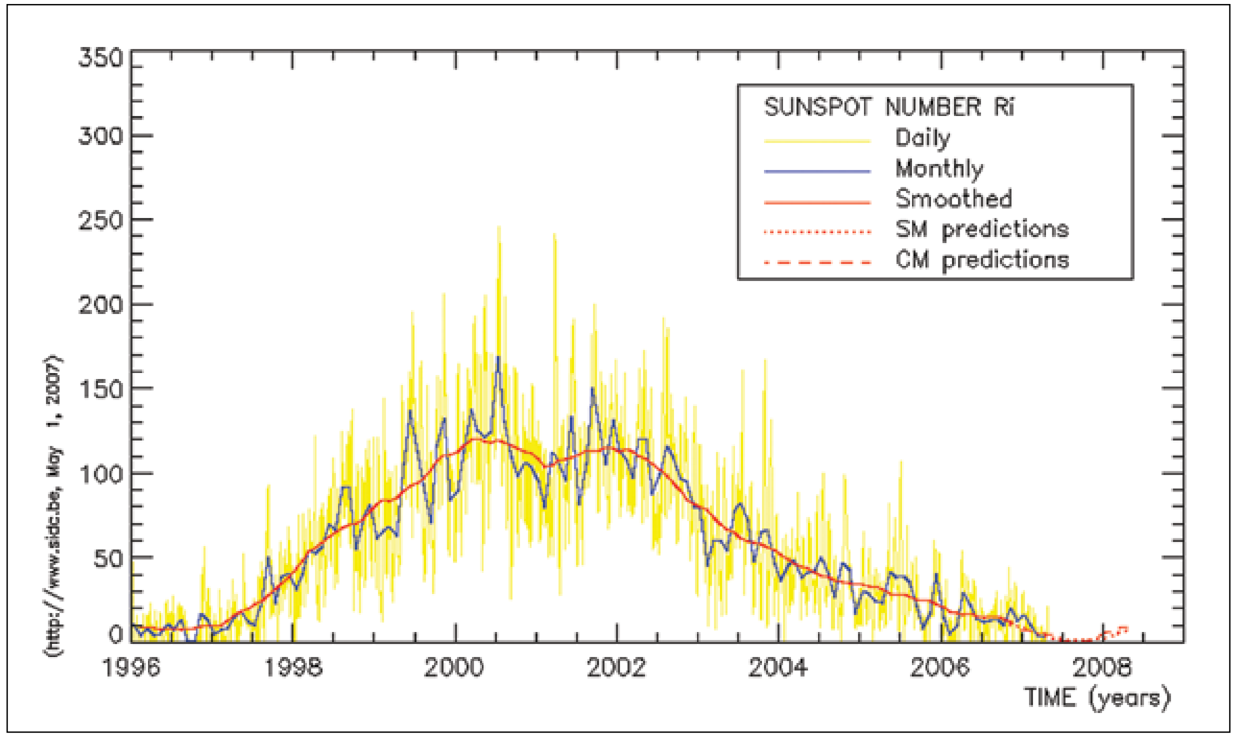


Figure 1. *Sunspot numbers covering a solar cycle, published by the Solar Influences Data Analysis Center.*

The facilities on La Palma, called the Observatorio del Roque de los Muchachos, house two solar telescopes: the 1-meter Swedish Solar Telescope (SST), managed by the Royal Swedish Academy of Sciences' Institute for Solar Physics, and the 45-centimeter Dutch Open Telescope (DOT), managed by Utrecht University's Department of Physics and Astronomy.

The SST saw first light in 2002 and was the first solar telescope in the world to use adaptive optics to reduce the effects of atmospheric distortion. Imaging the Sun through wide interference filters and through narrowband filters, the SST measures Doppler velocities of shifting magnetic fields and temperature variations throughout the solar atmosphere. "SST was the first to image with a spatial resolution of 0.1 arc-seconds, a sort of 'dream limit' for solar telescopes," said Göran Scharmer, the director of the Institute for Solar Physics, explaining that 0.1 arc-seconds equals about 75 kilometers on the solar surface.

Soon after first light, images from the SST revealed dark penumbral cores in sunspots (Figure 2) thought to be related to the strong flow of gas from the sunspot. In addition to producing several high-resolution movies of solar dynamics and maps of the Sun's magnetic field, SST observations have helped refine magnetohydrodynamic models of the Sun, especially parameters dealing with solar faculae, which are bright small-scale structures important for explaining variations in solar irradiance.

While most solar telescopes evacuate the gas surrounding the lens to avoid internal turbulence caused by heating, the DOT (p. 16) uses a system that relies on the air directly above the lens being flushed by the region's strong trade winds. Its main mirror can reach 0.2 arc-seconds in resolution and is specifically suited for studying the emergence and decay patterns of solar magnetic fields, the photospheric-chromospheric dynamic connection in nonmagnetic regions, and the fine structure of sunspots and prominences. Scientists from the University of Utrecht have also developed a method called "despeckling" by which DOT images are processed to enhance clarity of fine structures.

Tenerife's Tiede Observatory houses Germany's 70-centimeter Solar Vacuum Tower Telescope (VTT), operated by Freiburg's Kiepenheuer Institute of Solar Physics. Also with a spatial resolution of 0.2 arc-seconds, the telescope helped scientists retrieve high-quality measurements of solar plasma flows and magnetic fields. Able to simultaneously observe in different parts of the solar spectrum, the VTT can also construct the three-dimensional structure of the solar atmosphere. This year, VTT will be joined by the GREGOR telescope, which will be operated by a consortium of German institutions. With an aperture of 1.5 meters, it will be the most powerful solar telescope until Hawaii's Advanced

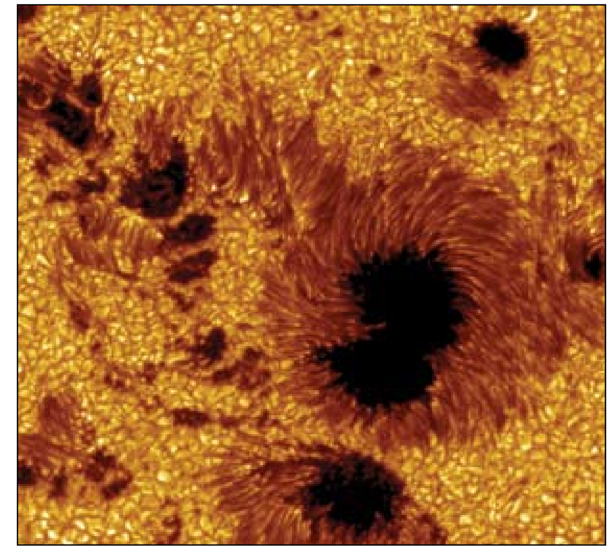


Figure 2. *Image of dark penumbral cores, collected by the 1-meter Swedish Solar Telescope, courtesy of Göran Scharmer and Mats Löfdahl, Institute for Solar Physics of the Royal Swedish Academy of Sciences.*

Technology Solar Telescope becomes operational [see *Kumar*, 2007]. Science goals include constraining an energy budget for sunspots and explaining the emergence, evolution, and disappearance of magnetic flux on the Sun.

The Télescope Héliographique pour l'Etude du Magnétisme et des Instabilités Solaires (THÉMIS), also at Tiede, is jointly operated by France and Italy. With a 90-centimeter aperture, its design allows for highly accurate spectral studies of the solar surface.

Tiede Observatory also houses SolarLab, a group of instruments geared toward studying the Sun's interior. One instrument, belonging to the Birmingham Solar Observations Network (BiSON), has been measuring solar oscillations formed by the propagation of pressure waves in the Sun through recording the Doppler shifts of photospheric emission lines since 1976. Other SolarLab instruments include a node of the Global Oscillations Network Group (GONG) [see *Kumar*, 2007] and a node of the Experiment for Coordinated Helioseismic Observations, both U.S.-driven helioseismology networks.

The suite of solar telescopes in the European Northern Observatory all provide information critical to space weather. "The main motivation is to map and understand the solar magnetic drivers," said Rob Rutten, a project scientist for DOT. "For DOT, a big question is how the photospheric magnetic elements connect into coronal loops and set their dynamics and energetics." Such information, combined with data from other ground-based studies of the solar interior and atmosphere, help refine space weather models and contribute to improving the predictive capacity of forecasts, he said.

Nobeyama Radio Observatory

Located near Nagano, Japan, the solar group of the Nobeyama Radio Observatory (http://solar.nro.nao.ac.jp/) was founded in 1969 by the Tokyo Astronomical Observatory and the University of Tokyo. In 1998, facilities were merged into the management of Japan's National Astronomical Observatory, joining with solar radio groups from Toyokawa Observatory and Nagoya University.

Main facilities consist of two arrays of telescopes, the Nobeyama Radioheliographs (NoRH) and the Nobeyama Polarimeters (NoRP). The NoRH is a network of 84 telescopes, each with 80-centimeter parabolas (Figure 3). As the largest microwave array in the world dedicated for solar studies, the array saw first light in 1992 and currently collects observations of the Sun's full disk normally every second, but during a solar event every tenth of a second, for 8 hours every day. These telescopes collect light at 17 and 34 gigahertz, which correspond to 10 arc-seconds (750 kilometers on the Sun's surface) and 5 arc-seconds (375 kilometers on the Sun's surface), respectively. The NoRP is an array of seven telescopes that measure the total flux and total circular polarization from the Sun at 1, 2, 3.75, 9.4, 17, 35, and 80 gigahertz. "The NoRPs are the most stable and reliable radio polarimeters covering the whole range of the microwave region," said Kiyoto Shibasaki, director of the Nobeyama Radio Observatory's solar group, adding that their archive of the Sun's total flux measurements is one of the longest.

Primary solar science targets at Nobeyama are to understand solar flares and eruptions with microwave imaging and intensity observations. "We detect prominence eruptions using images, and solar flares using images and total power calculations, and put them on the Web," explained Shibasaki, adding that other organizations use such data to characterize events and generate statistical studies on the frequency of such eruptions, information important to space weather modeling.

Observatories in Australia

The Australian Space Weather Agency (http://www.ips.gov.au/Space_Weather) maintains two solar facilities: The Culgoora Solar Observatory, in New South Wales, and the Learmonth Solar Observatory, in Western Australia.

The Culgoora Solar Observatory (CSO) houses three main instruments: a 12-centimeter solar telescope

Figure 3. *The Nobeyama Radioheliograph Array*

fitted with a hydrogen-alpha filter, used to observe solar flares; a 30-centimeter heliostat for observing sunspot evolution; and a solar radio spectrograph that observes through a frequency range of 18 to 1800 MHz every 3 seconds to monitor solar radio bursts. Though optical instruments were established at CSO in 1976, the observatory was already the home of a thriving solar radio astronomy research program dating from just after World War II.

Instruments established at the site made the first radio observations of a coronal mass ejection in 1967, and in the mid-1970s the radio spectrograph was one of the first instruments able to observe radio emissions from the Sun over a wide range of frequencies. Data from the radio spectrograph were vital to early space weather monitoring.

At the Learmonth Solar Observatory (LSO), founded in 1977, instruments include a 25-centimeter optical telescope and eight discrete frequency radio telescopes fed by three parabolic dish antennae. The radio telescopes do not record images, though data are digitized in real time. LSO also houses a node of the GONG network.

"LSO has provided the Australian Space Forecast Center with real-time data tailored to Australian requirements that have helped put [Australia] on the leading edge of space weather forecasting for the Southern Hemisphere and for the longitudinal hemisphere opposite to that covered by the U.S. Space Environment Center," explained John Kennewell, the principal physicist at LSO.

In particular, LSO continues work started by NASA's Solar Particle Alert Network, a program that was designed to support space weather monitoring during the Apollo spaceflight missions. According to Kennewell, the facility will also likely host a node of the Mileura Widefield Array, a project organized by the Massachusetts Institute of Technology and geared toward measuring and imaging coronal mass ejections and their movement through the interplanetary medium.

"Both the CSO and LSO are essentially real-time solar patrol observatories, and they supplied data via the World Data Centers to many researchers around the world," said Kennewell.

Space Climate

These observatories, as well as several others across the globe, are contributing to real-time monitoring of space weather, and are generating data that can be fed into models critical to space weather forecasts.

"Ground-based data recorded over multiple states represent the cheapest and most robust way to implement a long-term solar monitoring system," said ROB's Clette. Isolated instruments and especially space-based missions, by their short lifetimes and the absence of absolute calibration over long timescales, cannot address properly long-term issues, he explained.

"Long means tens of solar cycles—multicenturies. This is precisely where the permanent ground-based record now proves once again invaluable. In the process, a new field is emerging next to space weather: space climate," Clette added. "Just like for Earth weather and climate, we need both approaches to reach a global vision and understanding of the variable system of our Sun."

Mohi Kumar is a science writer for the American Geophysical Union.

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Reference

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